OBSERVATIONS ON TRANSITION OF THE UNSTEADY PIPE FLOW

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The stability of a fully-developed laminar pipe flow with a superimposed sinusoidal modulation has been studied in a straight water tube via LDA techniques. This study has identified the stability-instability boundary as that demarcating laminar and transitional flows in the three-dimensional parameter space defined by the mean and modulation Reynolds numbers $Re_m$, $Re_\omega$ and the Stokes parameter $\lambda$. Furthermore, this study documents the mean frequency of occurrence of 'turbulent puffs' as functions of $Re_m$, $Re_\omega$ and $\lambda$. This study also delineates the conditions when 'puffs' occur randomly in time as in the unexcited flow or phase-locked with the excitation. The periodic flow requires a new definition of the transitional Reynolds number $Re_{tr}$, which is defined on the basis of the rate of change of the puff frequency with $Re_m$. It is found that $Re_{tr}$ can increase or decrease from the corresponding steady flow value depending on $\lambda$ and $Re_\omega$. Modulating the flow sinusoidally can result in an increase of $Re_{tr}$ (by as much as 60% of the steady flow value of 2000), the maximum increase occuring at $\lambda \cong 5$. Very high $\lambda$ ($\gtrsim 70$) excitations produce only marginal effects on the instability of the flow. The experimentally obtained stability-instability boundary in the ($Re_m$, $Re_\omega$, $\lambda$) space is compared with theoretical results on the stability of the oscillating plane Poiseuille flow, the Stokes layer and the oscillating pipe Poiseuille flow. At high $\lambda$ values, when the Stokes layer thickness is considerably smaller than the pipe radius, a qualitative agreement is observed between experiment and stability theories. At low $\lambda$ values, our data agree qualitatively with two different theories based on quasi-steady flow. Previously reported observation of periodic breakdown of the unsteady flow into turbulence during the deceleration phase, followed by a relaminarization during acceleration, can be explained in terms of a new phenomenon: namely, periodic modulation of the pipe flow



results into a spatially periodic pattern of laminar and turbulent fluid 'patches' along the pipe length. Thus, depending on the distance of the measuring station from the pipe inlet, where the 'patches' originate, transition can occur at any phase of the oscillation. A preliminary study of the turbulent structure inside phase-locked turbulent 'patches' showed that a simple classification of these patches into 'puffs' or 'slugs' is not possible, contrary to the steady flow case. Additionally, the length of the 'patches' could be continuously increased from zero to the entire pipe length by increasing the mean Reynolds number. This tends to question the concept that all turbulent fluid patches (and eventually even the fully-turbulent flow) are the result of mutual interactions of many identical "basic building blocks" of a finite length.